1959

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Massachusetts Institute of Technology

http://hdl.handle.net/10945/14689

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OF A MILD WEAR PROCESS

by

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Submitted to the Department of Naval Architecture and Marine Engineering on 25 May 1959 in partial fulfillment of the requirements for the Master of Science degree in Naval Architecture and Marine Engineering and the Professional degree, Naval Engineer.

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Department of Naval Architecture and Marine Engineering, 25 May 1959

Certified by: ______________________
Thesis Supervisor

Accepted by: ______________________
Chairman, Departmental Committee on Graduate Students

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by

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ABSTRACT

The processes by which unlubricated mild wear occurs are not well-defined, and the sequence of events which leads to an equilibrium of these processes has been investigated using the mild steel pin-hardened steel ring geometry. Gravimetric weighing and radioactive tracer methods were used to follow wear particle history. In addition, the perturbation of intentional pin misalignment was imposed on the geometry to obtain further information.

The information collected from simultaneous employment of some, or all, of these techniques revealed the following:

A presentation of the various stages of this wear process can be made simultaneously visible.

A finite time elapses between the transfer of a particle and its subsequent oxidation.

In the absence of an intervening oxide film, it is possible to deposit wear material on previously transferred material.

Direct wear is a distinct possibility in the initial stages of wear.

Thesis Supervisor: Brandon G. Rightmire

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ACKNOWLEDGEMENT

The authors gratefully acknowledge the assistance they have received in doing this work. They are especially indebted to Professor Brandon G. Rightmire for his interest, advice and invaluable discussions.

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I. INTRODUCTION

Basic knowledge of the unlubricated wear process is necessary in the continuing investigation of wear of surfaces under minimal conditions of lubrication, such as the wear of bearing surfaces when starting, before hydrodynamic lubrication can be provided.

Much experimental work has been done to determine the mechanism of wear during a sliding process between two unlubricated surfaces. Kerridge (3), using radioactive tracer methods, has established that the wear mechanism between two dry, unlubricated steel surfaces is a four-stage process involving: (1) removal of material from the softer test piece by the forming of welded junctions, which in turn break off and adhere to the harder material, (2) the building up of a layer of this transferred material, but as a different hard form, (3) the oxidation of this layer, (4) the removal of the oxide to form wear debris. He has also shown that there is no direct wear and no back transfer for the materials and geometry used, and that the equilibrium wear rate is determined by the rates of formation and removal of the oxidized transfer material from the ring.

In Barrett and Gildea (4), Figures VIII and XXVII, runs using non-pre-worn and pre-worn pins, at the same conditions of load and speed, seem to result in greatly differing equilibrium transfer layers. Also, it is noted that in Figure XX of Barrett and Gildea (4) and in several curves of Vasques, Smith, and Boghossian (5), the initial transfer rate is higher than the initial wear rate. These discrepancies were due perhaps to experimental error, but most likely because both groups of

workers obtained their wear measurements using inactive pins and later measured transfer using radioactive pins. For these reasons it was planned to make further experiments to investigate the equilibrium transfer while making simultaneous wear and transfer measurements, using both pre-worn and non-pre-worn pins. It was hoped that during the course of these experiments, more details of the actual wear mechanism would be learned.

II. PROCEDURE

The apparatus used for these experiments was a Hardinge bench lathe adapted as a pin and cylinder wear machine. The apparatus was basically the same as that used by previous workers at M.I.T., references (4) and (5), and is illustrated in Figure I. The mild steel test pin was held in a loading arm which pivoted in ball bearings to allow accurate realignment after swinging the arm away for removal of the face-plate. The entire pin holding mechanism was attached to the lathe carriage. The cylindrical surface was provided by the hardened steel bearing cup which was mounted on the face-plate. The entire face-plate could be quickly removed from the lathe to make radioactive (transfer) measurements. The lathe, together with its variable speed Graham drive was mounted in a positive draft hood to reduce the radioactive hazard. The operating atmosphere was controlled by a shield surrounding the pin and cylinder during a test and to which was connected a supply of dry, oil-free, compressed air. The air was led from the tank through a copper coil immersed in liquid nitrogen and then through a sodium hydroxide dehumidifier to insure that no moisture remained in the operating atmosphere.

At the end of a desired length of time, the pin was removed and the wear measured by weighing the pin on a Voland chemical balance. To measure the amount of transferred metal on the ring, radioactive pins were run on the ring. The face plate, with the ring, was removed from the lathe at desired intervals and placed

on a vertical spindle mounted in an inverted drill press. The face plate assembly was rotated at a constant speed before a Geiger-Muller tube which was accurately positioned 1/16 inch from the ring. The entire assembly was surrounded by a lead castle which greatly reduced the background activity (Figure II). The Geiger-Muller tube, with its attendant scaler, recorded the counts per minute produced by the active material transferred to the ring. This count was compared with a known amount of similar material deposited on a similar ring as described in Appendix A. In this manner the amount of material transferred to the ring during the test was determined.

Before each test the speed of the lathe was carefully checked with a tachometer. Both the pin and cylindrical surfaces were finally cleaned by two successive applications of acetone to remove any oil or grease. It was felt that any effect of the acetone film would be minor because the film would be immediately worn off at the start of a test. This view is also held by Archard and Hirst (12). Further, if emery paper or some other abrasive were used to remove the acetone film, there would be a possibility of extraneous abrasive particles interfering with the wear mechanism.

The pins were irradiated at the Massachusetts Institute of Technology Reactor.

An analysis of the mild steel pins showed the following composition:

Carbon	.13%
Phosphorus	.102%
Sulphur	.223%
Manganese	.90%
Silicon	.09%
Nickel	0
Chromium	0
Molybdenum	0
Iron	98.55% (Balance)

These pins consisted of 3/4 inch long pieces cut from 1/4 x 1/4 inch stock. Their hardness was 97 Rockwell B. The ends were hand lapped and given a final finish on 4/0 emery paper.

The rings were standard Timken bearing cups #3623, 2.5 inch O.D., width .6875 inches. Their hardness was 62 Rockwell C. To insure uniform surface conditions on the rings, no effort was made to obtain a smoother surface than that provided in manufacture. This particular bearing cup was identical to that used by Barrett and Gildea (4) and permitted qualitative comparison of results with this reference.

III. RESULTS

All tests were run at a load of 500 grams and a rubbing speed of 542 RPM (180 cm/sec).

WEAR RATE

In all tests using both pre-worn and non-pre-worn pins, a relatively high initial wear rate was obtained followed by a transition and a lower final wear rate. This is in agreement with the results obtained by Archard and Hirst (12) who find that the wear rate often changes with time during the early stages of rubbing followed by a constant wear rate after the surface layers have attained their equilibrium conditions. It was noted that for pre-worn pins, the equilibrium wear rate was reached after a shorter rubbing distance than for non-pre-worn pins. See Figure IV. Note that the equilibrium wear rate had apparently not been reached after 75 minutes for run 7, and that it was reached after about 90 minutes on run 2. Reproducibility of the equilibrium wear rate was within experimental error. The equilibrium wear rate amounted to about 0.1 mg/min.

It was noted that with non-pre-worn pins, slight misalignment produced a parabolic wear scar which continually expanded over the rubbing surface of the pin as the test progressed. During the early stages of wear, three bands were noted on the wear scar (Figure III). At the apex of the parabola, the pin material experiencing its first contact with the ring appeared shiny to the eye but under a microscope appeared to be cut or gouged out by the harder ring material. The second band was bluish-grey in appearance. The third band had

a rusty red appearance which, when viewed under a microscope, could be attributed to fine, loose, oxided material lodged between the asperities of the pin surface. The surface of the red band was relatively smooth compared to that of the grey area. There was a sharp, well-defined transition between the rusty and grey bands. It will be shown that the grey band is linked with the high initial wear rate and is similar to the severe wear described by Archard and Hirst (12,13), while the rusty band is associated with the equilibrium wear condition, and is similar to mild wear as described in the above references.

TRANSFER

The initial alignment has a marked effect on the initial amount of transfer to the ring. The poorer the alignment, the greater the maximum amount of transfer and the time required to reach equilibrium transfer. See Figure X.

Figure X also shows that regardless of the initial transfer rate and the maximum amount of transferred material, all curves approach the same value, the eventual equilibrium appearing to be about 0.65 mg. The "hump" centered at about 100 minutes of run 4 is due to different intervals between measurements. At 100 minutes the interval of measurement was changed from 10 to 30 minutes. This allowed the transfer layer to reach a higher average temperature before cooling during measurement. Steijn (10), for a different geometry, has shown that a relatively small rise in the harder surface temperature (10°F above room temperature) permits the oxide to be much more easily rubbed off. During this period of reduction of the total transferred mass to the eventual

equilibrium value, the average size of the oxidized particles is greater than the size of the new transfer particles wearing from the pin. Therefore, a more rapid removal of the oxide during this period resulted in the increased slope of the transfer curve. This same effect probably escaped detection on other runs because none attained such a high initial transferred mass value and, therefore, these runs were much closer to equilibrium conditions.

Again reproducibility appears good, with the same pre-worn pin running on two different rings (runs 5 and 6) resulting in the same amount of transfer (within experimental error) after about 80 minutes and run 10, with a different pin, approaching very closely to equilibrium transfer conditions after 2 hours.

As pointed out by Kerridge (3), the wear rate, after equilibrium conditions have been established, is determined by the rate of removal of the oxidized transfer material. To investigate further, on run 7, Figure VII, part of the transfer layer was rubbed off after 60 minutes running time by using a hardened steel drill rod. The drill rod was substituted for the pin and run for one minute at the same load and speed; it did not wear appreciably, so that little, if any, transfer resulted. The drill rod was located at the middle of the transferred layer and removed a cylindrical portion of the transferred material, the width of removal being about one-third of the total transfer layer. The radioactive pin was then replaced and wear continued. The amount of transferred material increased rapidly, then fell off, presumably to continue the gradual decrease to the equilibrium

transfer conditions. This rise was entirely due to the portion of the artificially removed transfer layer. Associated with this increased transfer rate, the characteristic bluish grey area appeared faintly, but distinctly, on the pin and the wear rate apparently increased slightly from the previously established wear rate. This apparent increase in wear rate was not conclusive since the wear and transfer had not yet reached equilibrium. This experiment also contributed substantial weight to the argument that new wear material can be deposited on previously transferred material.

To investigate the effect of the pin on the transferred layer, the pin which had previously reached equilibrium conditions on run 6 was substituted for the original run 7 pin at 80 minutes, Figure VII. This pin caused a rapid reduction in the transfer layer, and itself experienced a slight increase in its wear rate. The transfer curve quickly leveled out and presumably would continue to equilibrium conditions had the test not been stopped for lack of time.

Since the above tests were conducted at non-equilibrium conditions, the procedure of artificially removing part of the transfer layer was repeated at near-equilibrium conditions using the same pin running on a different ring (run No. 10, Figure VIII). Qualitatively, the transfer layer showed the same effect; however, no increase in wear rate was noted. This effect on wear rate is inconclusive from these tests. This subject will be discussed further in Section IV.

The transfer portion of runs 7 and 10 are plotted together on Figure IX for ease of comparison.

RELATION BETWEEN WEAR AND TRANSFER

The above tests show that the condition of the pin has a definite effect on the transfer rate, and that the condition of the transfer layer largely determines the wear rate, as well as the net transfer rate.

Initial wear rate is, in each case, greater than the initial rate of buildup of the transfer layer by a factor of two or more, Figures VI, VII, and VIII. This indicates that direct wear is a distinct possibility in the initial stages of wear for these experiments, and can be associated with the shiny band of the misaligned initial wear scar mentioned previously.

IV. DISCUSSION OF RESULTS

At an early point in the experimentation, a non-pre-worn pin was accidentally misaligned. During this run, a parabolic wear scar was produced, which continually expanded over the rubbing surface of the pin as the test progressed. During the early stages in this misaligned run, three bands were noted (Figure III). At the apex of the parabola, the pin material experiencing its first contact with the ring appeared shiny to the eye, but under a microscope appeared to be cut or gouged by the harder ring material. The second band was bluish-grey in appearance. The third band had a rusty red appearance which, when viewed under a microscope, could be attributed to fine, loose, oxide material lodged between the surface asperities of the pin. The surface of the red band was relatively smooth compared to that of the grey area. These bands were discrete and well-defined. It was felt that a band reflected, in some way, the condition of the transfer layer which ran beneath it. It was also noted that these bands progressed across the wear scar, so that the final condition of the pin surface was that of the red band previously described.

When a pin was perfectly aligned, no bands appeared, and the entire rubbing surface was in the same condition at any one time. If the assumption is valid that bands may be linked to the condition of the transfer layer, misaligned pins should make possible simultaneous experimental study of the different phases of the wear process for these tests. Therefore, pins were deliberately misaligned, and a more detailed investigation of this phenomenon was made.

MISALIGNED PINS

The shiny area appeared at the very outset of a test, and progressed across the face of the pin, always being at the apex of the wear scar. The cut, or gouged appearance noted under the microscope has two possible explanations. One - that loose surface particles, which were not removed during the surface preparation of the ring, or were "picked up" subsequent to mounting, abraded the initial pin contact area. After a few revolutions, these particles would have been removed by the rubbing process. The second possible explanation is that the surface asperities of the much harder ring actually sheared pin material from the initial contact area. In conjunction with this explanation, it should be noted that the maximum surface roughness of the rings used is given by Timken Co. as 50 micro-inches r.m.s. In the opinion of the authors, the second explanation is to be preferred. It will be shown later that there is a distinct possibility of direct wear occurring during the initial stages of wear. If direct wear actually occurs, it is associated primarily with the shiny area. It is supposed that the load is not carried by the shiny area, but rather by the adjacent areas which have already built up a transfer layer through the welding and tearing off of surface asperities. At no time was the shiny area noted by itself. If the shiny area carries none or very little of the load, it is not surprising that the bluish-grey characteristic of the load-supporting area is absent here. The supposition that direct wear occurs during the initial stages is supported by the presence of relatively large, shiny, metallic particles found with the normal wear detritus.

The bluish-grey area always followed the shiny area as the apex of the wear scar progressed across the pin. The appearance of this area corresponds to the severe wear described by Archard and Hirst (12,13). Here, the probability of asperity contact, and subsequent welding, is high, since the ring is relatively clean; further, the pin surface is rougher and large individual transfers are probable. These processes tend to be self-sustaining. Catastrophic build-up is prevented by the continued rubbing of the transferred particles which causes them to smear out. This is borne out by microscopic examination of the layer of transferred material corresponding to this band. As the areas of contact change, a complete layer is gradually built up. The bluish-grey color on the pin is presumed to be a consequence of the high temperatures occurring at asperity contacts.

The transition from the bluish-grey band to the red band was extremely well-defined. The wear grooves in the red band were much more closely spaced than in the bluish-grey. The average grey spacing was approximately five times that of the red. The change from grey to red was discontinuous, as far as could be determined with the microscope, and it is this "discreteness" which clarifies the mechanism of oxidation in the wear process. From microscopic inspection, it was determined that the reddish appearance of this band was due to a fine dust, lodged between asperities on the pin surface, which could be readily blown off, revealing the bluish-grey color characteristic of overheating in the welding type transfer. This was obviously oxidized material from the transfer layer. It would seem that oxidation

is time dependent, as well as temperature dependent, otherwise the transfer layer would have oxidized immediately as a result of the high temperatures experienced during the welding process. Since a large portion of the transferred material on any circumferential line was deposited within a short time interval, it follows that the conditions for oxidation will be fulfilled simultaneously along that line. It is this oxide film which prevents further transfer at a given point until it is removed from the layer.

As long as the pin continues to show a grey area, the wear rate remains relatively high. Since the grey region is carrying the major portion of the load, the red region must carry a smaller portion of the load, and the grosser asperities now in the red region are gradually worn away, producing the finer finish previously noted.

It has been observed that the final equilibrium wear rate is not attained until the entire wearing area is red.

WEAR RATE

It was noted that non-pre-worn pins did not attain an equilibrium wear rate as fast as the pre-worn pins. The pin for run 7 (Figure IV) had not attained an equilibrium wear rate in 75 minutes, however, an additional 60 minutes running time on a new ring showed that an equilibrium wear rate had been attained in approximately 100 minutes running time. This agrees with non-pre-worn run 2 (Figure IV), where an equilibrium wear rate was reached in about 90 minutes. The apparent break in the wear rate on run 2, between 150 and 170 minutes, occurred at the

same time that the leading and trailing edges of the wear scar reached the edges of the pin. Presumably, some larger pieces of the pin material, contained in the thin edges, were worn or broken off.

In Figure IV, it may be seen that the equilibrium wear rates were reached in a substantially shorter time for pre-worn pins than for non-pre-worn pins. The initial wear rates were of the same order of magnitude for both types of pins. The higher initial wear rates, in each case, were associated with the presence of the bluish-grey area on the pin surface. However, for the pre-worn pins, the scale of damage was not as great as for the non-pre-worn pins as a result of the transfer of material from the full width of the pin surface. This leads to the conclusion that the size of individual transfers was smaller. Since the modifying effect of oxidation occurred in the same total time, but over the entire width of the transferred surface, while the transfer per unit area was reduced, the maximum amount of transfer is less for the pre-worn condition.

TRANSFER

The high initial amount of transfer associated with non-pre-worn runs 4 and 7, Figure X, was due to the transfer of large particles before oxidation intervened. As previously explained, the rate of replacement is determined solely by the rate of removal of the oxide. As the larger particles are oxidized and removed, they are replaced by the smaller particles associated with the mild wear process. This accounts for the gradual reduction in the mass of transfer until the equilibrium

transfer, associated with this particular load and speed, is reached.

Referring to Figure X, it can be seen that relative alignment is a strong factor in determining the maximum mass transfer, but that it has no effect on the eventual equilibrium transfer.

Since it has been shown that oxidation takes a finite time to appear after transfer, and in this time, for the misaligned pins, much more than the equilibrium layer must have been transferred to the ring, the obvious conclusion is that oxidation, through its rate of removal, not only controls the equilibrium wear rate, but that, through its rate of formation, prevents a continuing build-up of the transferred layer. For this to be true, the oxide, when first formed, must be relatively adherent. As mentioned previously, Steijn (10) shows experimental results which seem to support this view. For a continual build-up of the transfer layer to be possible, new wear material must necessarily be deposited on previously transferred material. Experiment has shown that this action can occur, as will be discussed later.

It has been shown by Kerridge (3) and others that an inert atmosphere reduces the equilibrium wear rate, but to our knowledge, no one has reported the effect on the equilibrium transfer layer of a reduction in oxidizing properties of the atmosphere in which two steel surfaces are rubbing. The above theory indicates that the equilibrium transfer mass under these conditions would be greater. Again, Steijn (9) gives support to this argument, but for brass on steel in a different geometry.

Future investigation using an inert atmosphere for this geometry and materials would be useful in the study of the equilibrium transfer layer. At the same time, more light may be shed on the bands noted in misaligned pins.

The temperature dependence of wear rate, equilibrium transfer mass, and rate of formation and removal of the oxide, should be investigated in the future.

As was mentioned in Section III, part of the transfer layer was artificially worn off for runs 7 and 10 (Figure IX). After the pin was replaced and the run continued, a grey band resulted on the pin surface over the immediate area where the portion of the transferred layer had been removed. Theory predicts that the wear rate should have increased; however, in a period of five minutes after pin replacement, the transfer mass increased by 0.17 mg (run 7). During this same period, the wear was 1.6 mg. Since the scale precision, in measuring this wear, was no better than plus or minus 0.1 mg, it is not surprising that the increase in wear rate could not be detected. It is significant that the bluish-grey band could be artificially produced, showing that this phase is associated with a high transfer rate and, presumably, a higher wear rate. Since the portion which was artificially removed exposed an unoxidized surface, a higher rate of transfer could take place in this area until oxidation again modified the phenomenon as previously described. Since the onset of oxidation again takes a definite time to appear, the higher rate of transfer associated with the condition to which the scraped area had been returned allowed the transfer layer to regain a

larger total mass. In fact, this small area of high transfer held, in the 75th minute, a larger mass than the previous maximum at 20 minutes. As transferred material was added to the artificially worn area, it accepted successively larger portions of the load, and it was noted on the pin surface that the scale of damage became more severe. The slight decrease in transferred mass, at two minutes after pin replacement, can be explained as follows: the unaltered portion of the transfer layer immediately accepted the total load, and the associated portions of the pin had to wear in the normal manner before contact could be made with the altered surface. These same effects were essentially duplicated in run 10, see Figure IX.

This experiment also contributes convincing experimental evidence that new wear material may be transferred to material already deposited on the ring. When the transfer layer was partially removed with the drill rod, it was visually noted that the part of the transfer layer which had been altered was as continuous as the unaltered portion, implying that the significant change in the altered area was a reduction in thickness. From this it may be deduced that the area of transferred material in the altered portion was essentially unchanged. When the pin was replaced, and contact occurred with the altered surface, a transfer rate resulted which was the same as that of the pin in the initial stage of wear. From this it must follow that some of the wear material was deposited on previously transferred material, since the accuracy in measurement of transfer rate is considered excellent.

The effect of pin surface condition is demonstrated at 75 minutes on run 7 (Figure VII). At this time, the pin that had previously run to near-equilibrium conditions on run 6 was substituted. This pin had a smoother surface than the pin for which it was substituted, and as a consequence, would produce smaller individual transfers in replacement of the removed oxide. A sharp drop in the total transferred mass was anticipated and noted. This substituted pin quickly reached equilibrium with the existing transfer layer, after which the transfer layer continued its moderate approach to final equilibrium.

DIRECT WEAR

Direct wear may be defined as the formation of wear debris directly from the softer material. Kerridge (3) has shown that there is no direct wear at equilibrium conditions. It has been shown above that it takes a finite time for an individual transfer to oxidize and be removed. If this is true:

$$R_{dw} = R_w - R_t \tag{1}$$

where R_w is the initial wear rate, R_t is the initial transfer rate, and R_{dw} is the initial direct wear rate. Noting Figures VI, VII, and VIII, the following table may be constructed:

TABLE I

Run No.	Type	R_t	R_w
6	Pre-worn	.2 mg	.36 mg
7	Non-pre-worn	.2 mg	.6 mg
10	Pre-worn	.04 mg	$>$.15 mg

While the quantitative accuracy may be questioned, it is felt that the accuracy of measurement was good enough to permit the qualitative conclusion that direct wear occurs in the first stages of wear. For misaligned pins, direct wear has been linked to the shiny area of the initial wear scar. Since direct wear was concentrated here, it was easily recognized from the pin appearance. It is probable that no visual evidence of direct wear for the pre-worn pins was noted because it was spread over a large area resulting in both smaller direct wear particles and reduced concentration.

More experimentation on this subject is recommended, and in this connection, a more finely surfaced ring should be employed to determine the effect of the initial hard surface on direct wear as well as the bands noted on the misaligned pins.

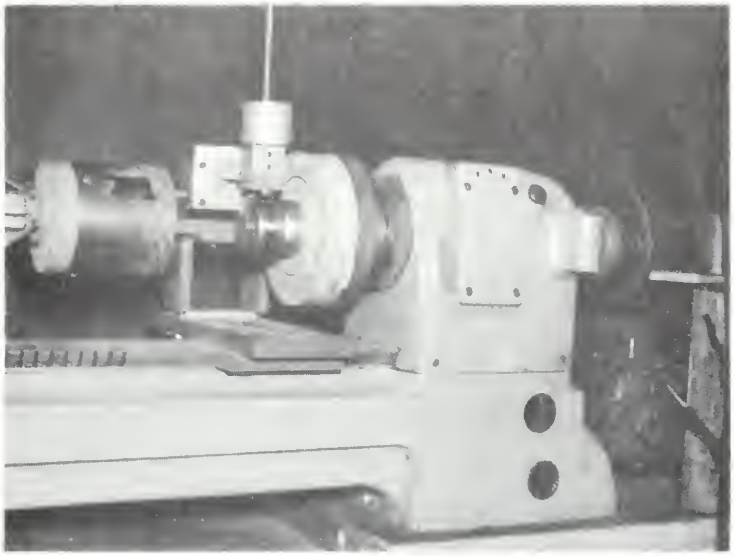


Figure I

Lathe with cylinder and pin loading device

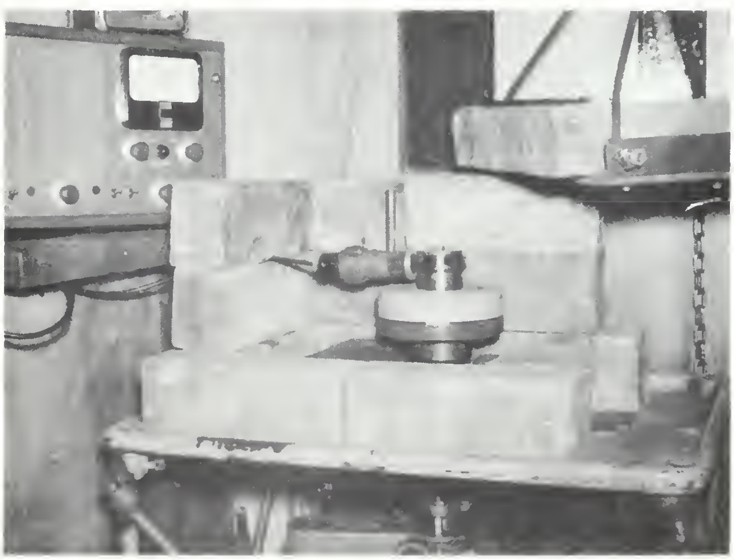


Figure II

Lead castle with top and two sides removed;
Scaler at upper left.

FIGURE III

TYPICAL MISALIGNED PIN

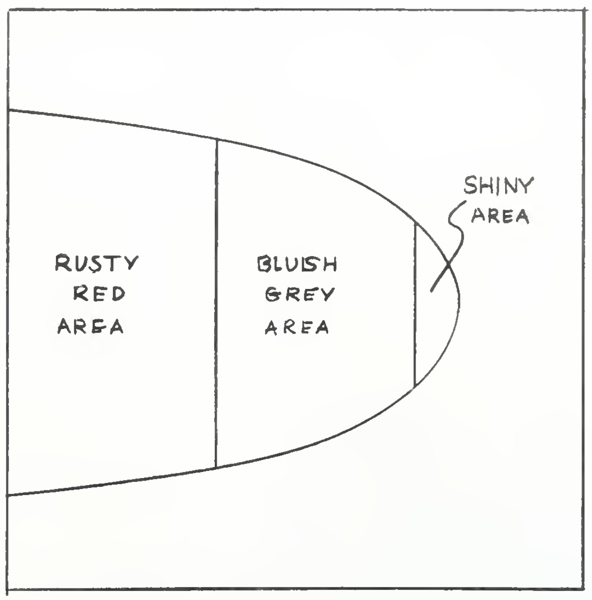


FIGURE IIIA

TYPICAL WEAR SCAR
ON MISALIGNED PIN

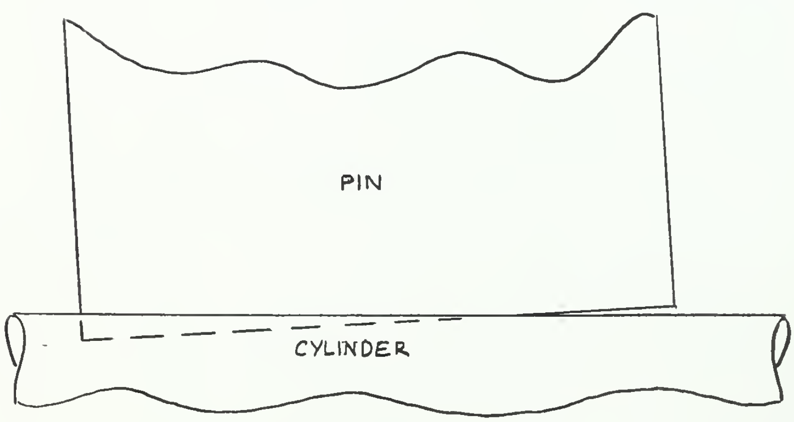


FIGURE IIIB

CONTACT BETWEEN MISALIGNED
PIN AND CYLINDER (EXAGGERATED)

FIGURE IV

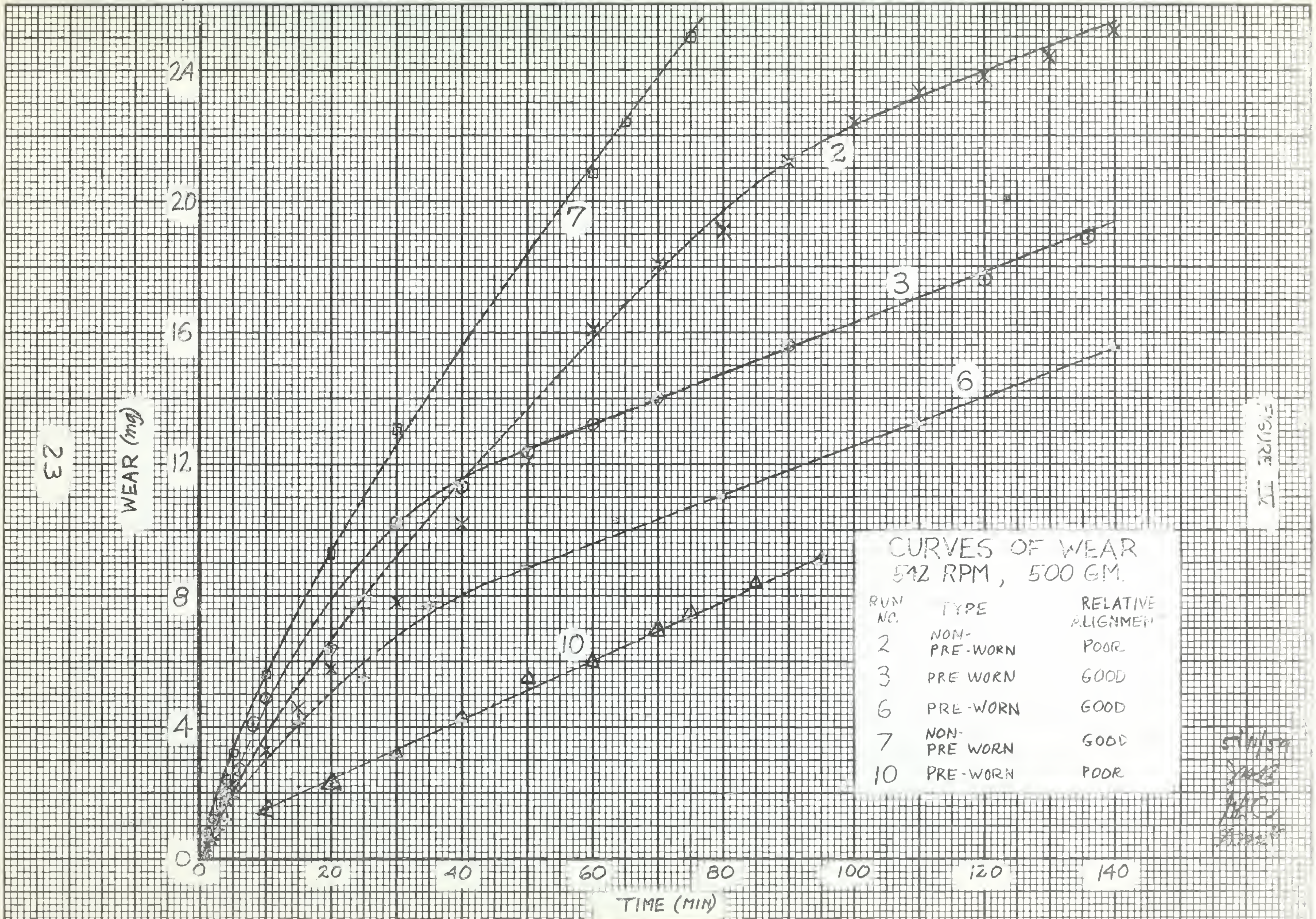

CURVES OF WEAR
512 RPM , 500 GM.
RUN NO.
TYPE
RELATIVE ALIGNMENT
2 NON-PRE-WORN POOR
3 PRE WORN GOOD
6 PRE-WORN GOOD
7 NON-PRE WORN GOOD
10 PRE-WORN POOR
WEAR (mg)
TIME (MIN)
0
4
8
12
16
20
24
20
40
60
80
100
120
140
2
3
6
7
10

FIGURE V

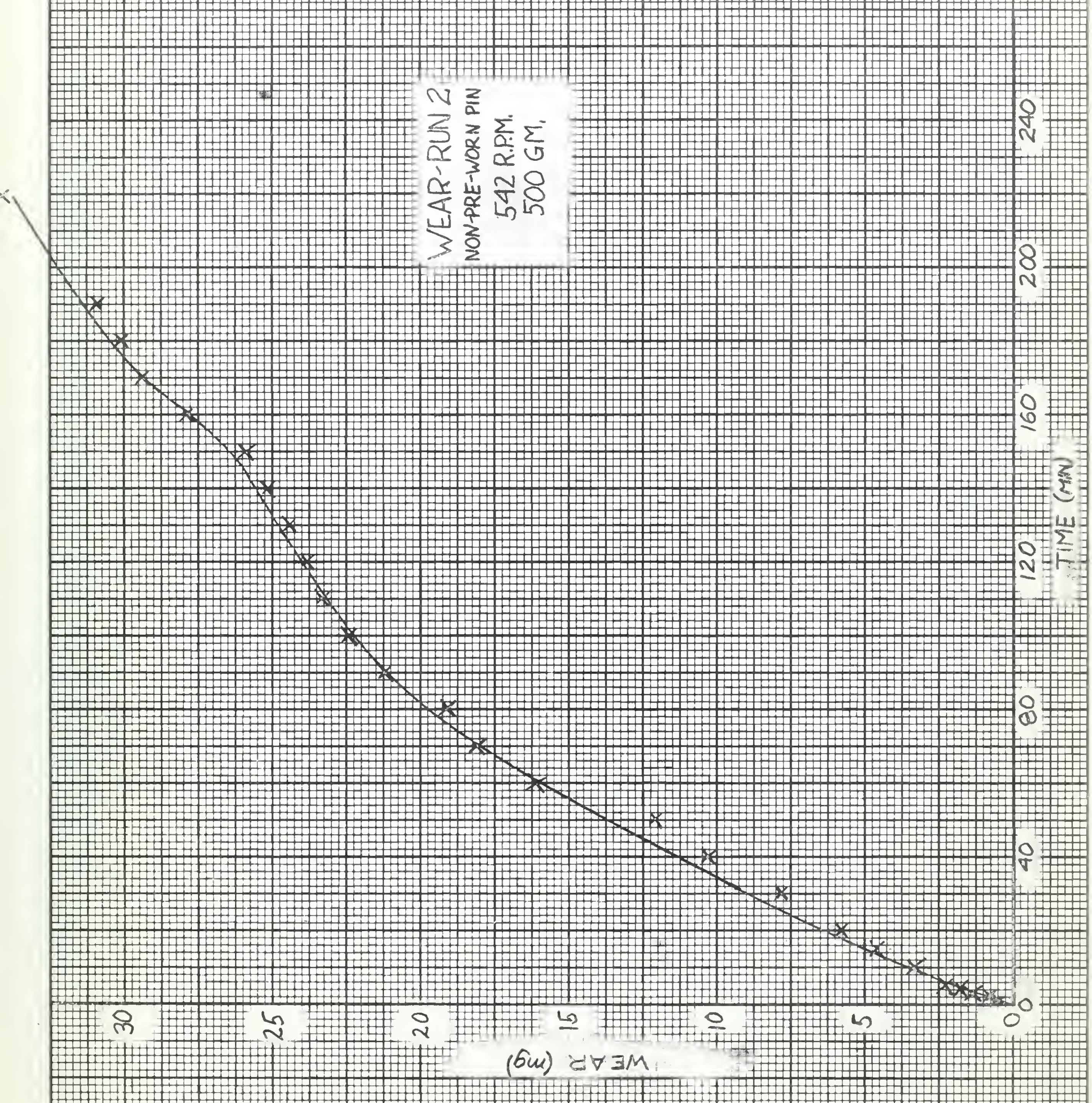
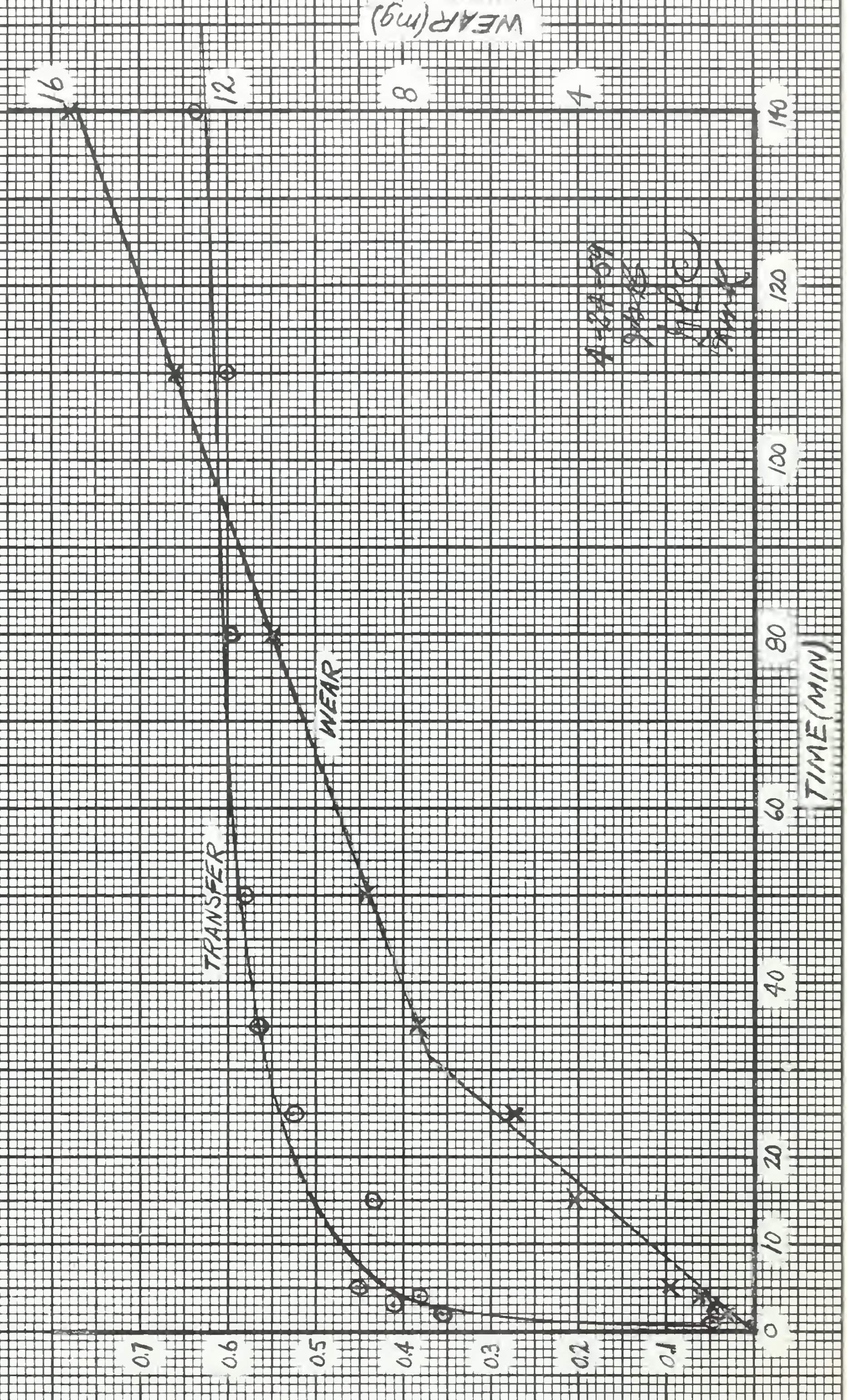
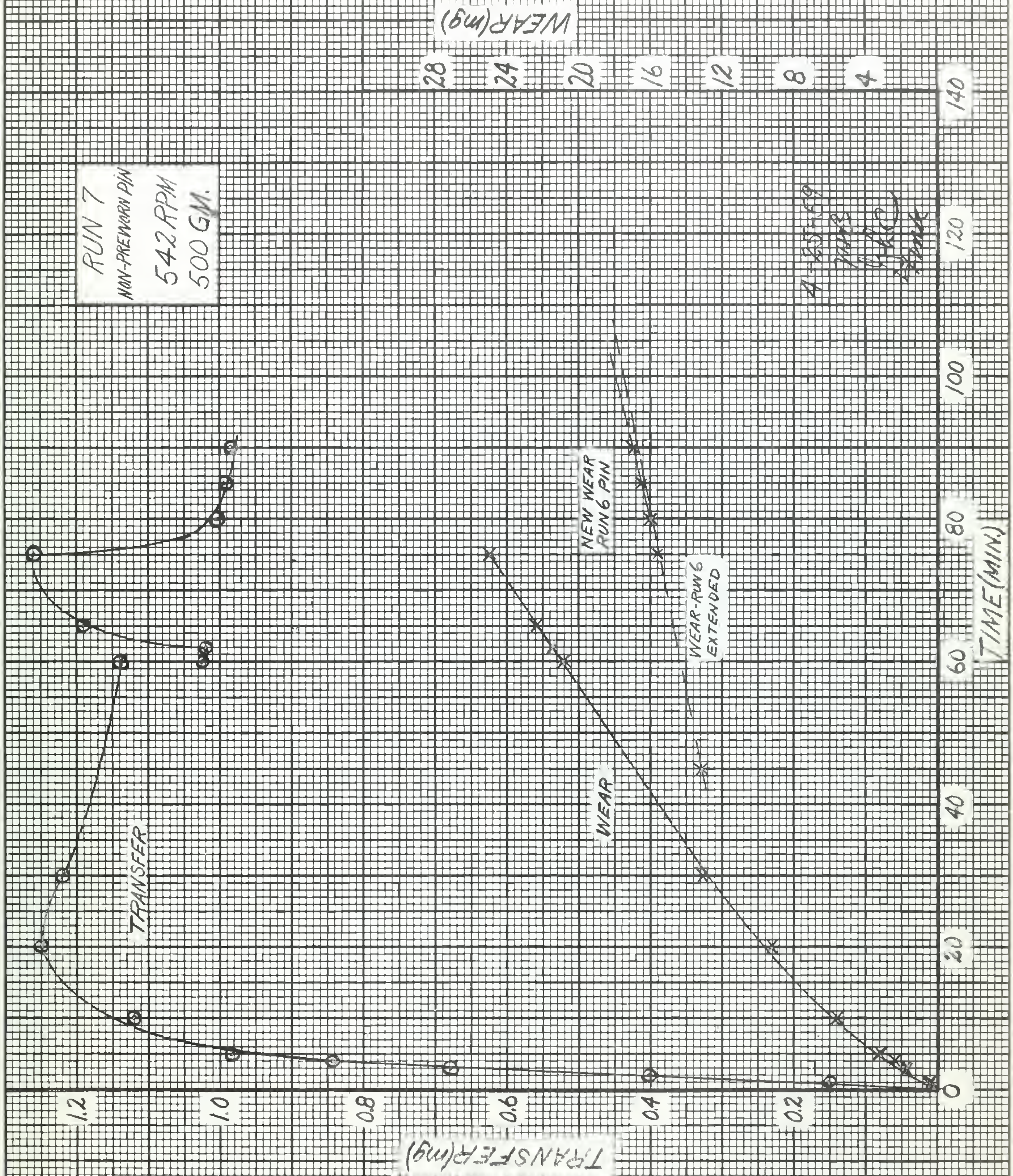

WEAR-RUN 2
NON-PRE-WORN PIN
542 R.P.M.
500 GM.
TIME (MIN)
0
40
80
120
160
200
240
WEAR (mg)
0
5
10
15
20
25
30

FIGURE VI



RUN 6
PREWORN PIN
542 RPM
500 GM.
WEAR(mg)
16
12
8
4
TRANSFER(mg)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
TIME(MIN)
0
10
20
40
60
80
100
120
140
WEAR
TRANSFER
4-24-59

FIGURE VIII



WEAR (mg)
28
24
20
16
12
8
4
RUN 7
NON-PREWORN PIN
542 RPM
500 GM.
4-25-49
NEW WEAR
RUN 6 PIN
WEAR-RUN 6
EXTENDED
WEAR
TRANSFER
TIME (MIN.)
0
20
40
60
80
100
120
140
1.2
1.0
0.8
0.6
0.4
0.2
TRANSFER (mg)

FIGURE VIII

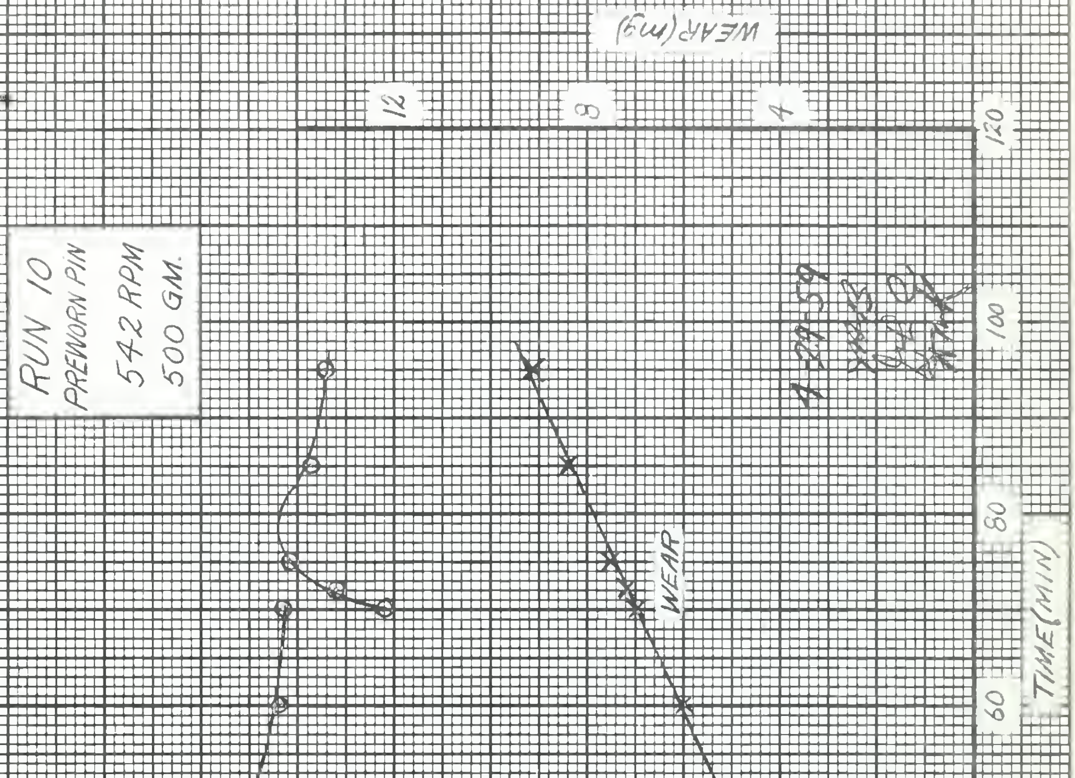
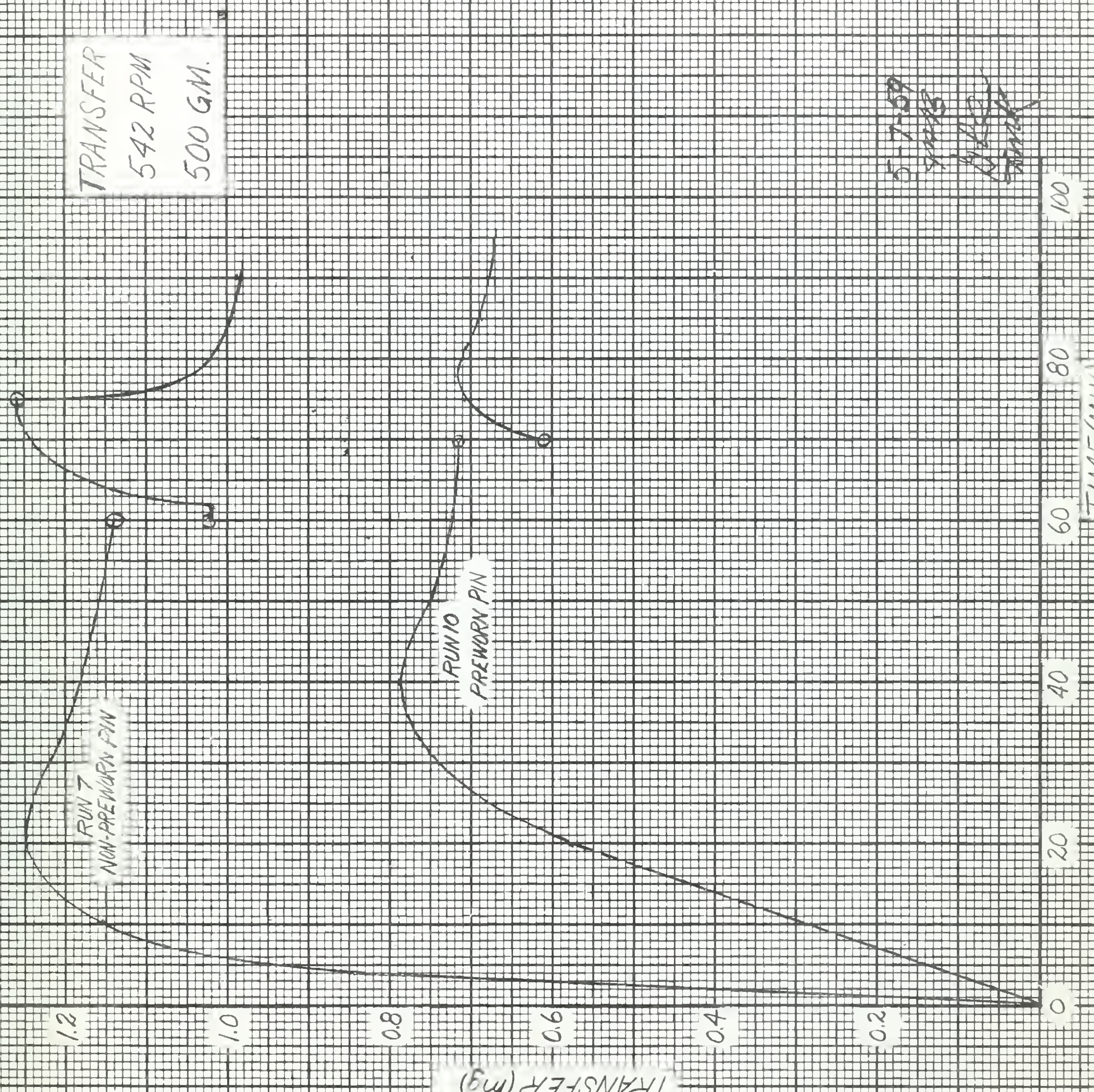
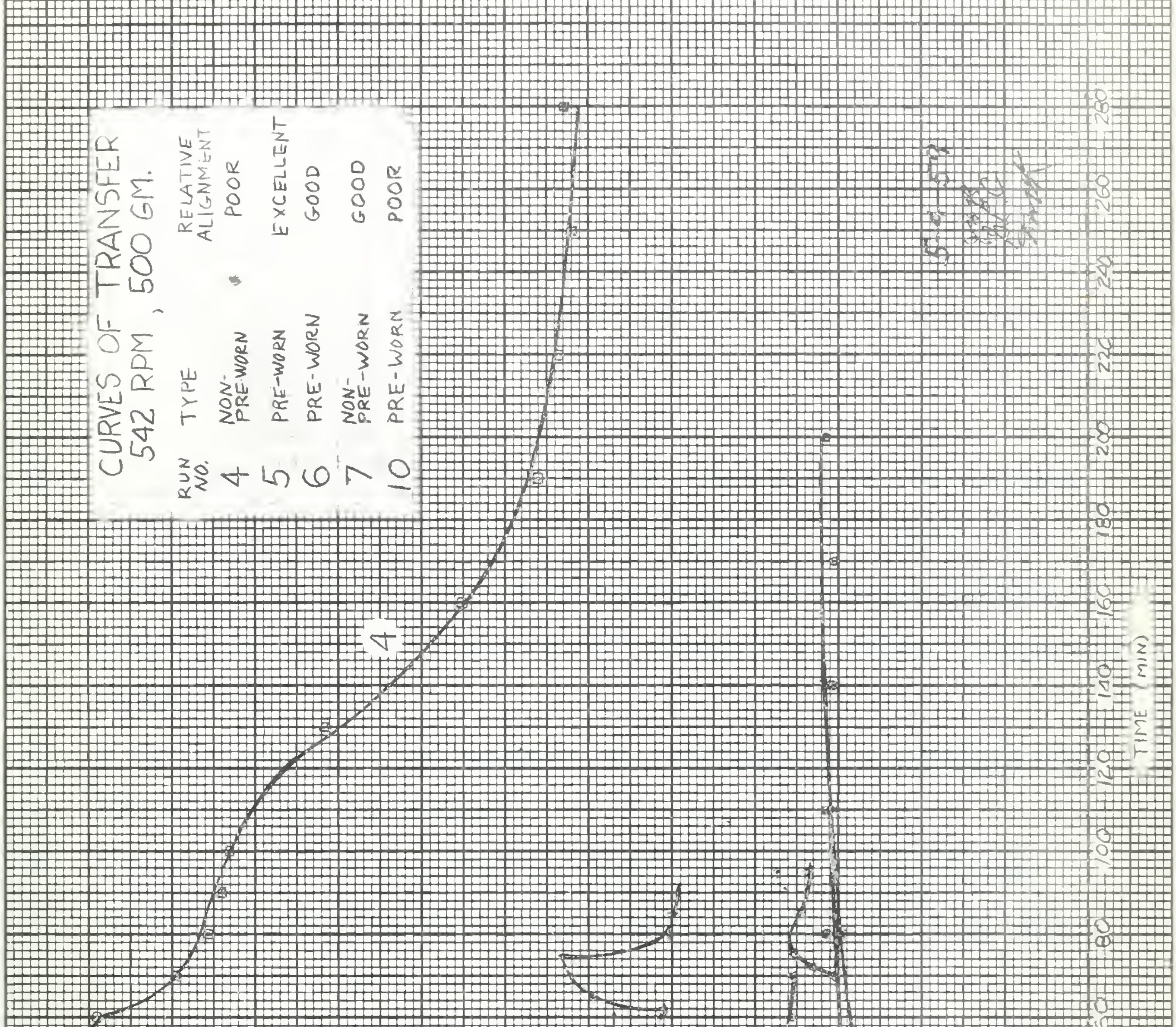

WEAR(mg)
12
8
4
RUN 10
PREWORN PIN
542 RPM
500 GM.
4-29-59
TRANSFER
WEAR
120
100
80
60
40
20
0
TIME(MIN)
0.8
0.6
0.4
0.2
TRANSFER(mg)

FIGURE IV



TRANSFER
542 RPM
500 GM.
RUN 7
NON-PREWORN PIN
RUN 10
PREWORN PIN
TIME (MIN.)
0
20
40
60
80
100
TRANSFER (mg)
0.2
0.4
0.6
0.8
1.0
1.2

FIGURE X



CURVES OF TRANSFER
542 RPM, 500 GM.
RUN NO. | TYPE | RELATIVE ALIGNMENT
4 | NON-PRE-WORN | POOR
5 | PRE-WORN | EXCELLENT
6 | PRE-WORN | GOOD
7 | NON-PRE-WORN | GOOD
10 | PRE-WORN | POOR
TRANSFER (mg)
TIME (MIN)
0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280
4
7
10
6
5

V. CONCLUSIONS

1. These tests show that simultaneous measurements of wear and transfer are both possible and highly desirable.
2. Misaligned pins reflect the various stages of the wear process simultaneously and present a vivid contrast between these stages. This simultaneous presentation of the stages of wear yields both qualitative and quantitative information on the wear process, which would otherwise be most difficult to obtain.
3. The initial relative conformity of the pin-ring combination has a strong influence on the time required to reach equilibrium conditions, and in determining the maximum amount of mass transferred, but has no effect on the eventual equilibrium conditions.
4. A finite time elapses between the transfer of a particle and its subsequent oxidation.
5. Oxidation of the transferred layer prevents a continuing buildup of the transfer layer. This oxidized layer is not easily removed when first formed.
6. In the absence of an intervening oxide film, it is possible to deposit wear material on top of previously transferred material.
7. The initially higher wear rate exhibits the characteristics of "severe" wear described by several authors. (References 12, 13.)
8. Direct wear, in the initial stages, is a distinct possibility. The initial surface roughness and hardness of the

harder material are likely influences in producing direct wear.

VI. RECOMMENDATIONS

1. A more detailed study of misaligned pins should yield valuable details of the wear process, among which is the time required for a transferred particle to oxidize. Autoradiographic techniques, in conjunction with misaligned pins, should be useful in following the history of transferred particles.
2. The existence of direct wear should be further verified. In this connection the effect of more finely surfaced rings should be investigated.
3. Experimentation should be carried out in an inert atmosphere to further investigate the effects of oxidation, particularly its effect on the equilibrium transfer layer.
4. The temperature dependence of oxidation should be explored by attempting to relate the transition from initial to final wear with environmental temperature.

VII. APPENDIX

APPENDIX A

ESTABLISHING A RADIOACTIVE STANDARD

It is obvious that the quantitative accuracy of the transfer measurements is dependent upon the establishment of an accurate standard. The overall procedure for creating a standard consists of placing a known mass of radioactive pin in a geometry which is made as similar as possible to that geometry which exists for the transfer layer. If the assumption is made that the pin used for making the standard has attained the same level of activity as the pin used in the transfer run, then the mass transferred in each case will be directly proportional to the activity of each mass.

The pins involved were irradiated simultaneously in the M.I.T. reactor. In order to attain uniformity of irradiation, the pins were oriented identically in a 15/16" D. container over a vertical height of 2-1/4". The vertical position of each pin in the container was recorded to furnish information in the event that the irradiated pins should show non-uniform activity. However, the irradiated pins showed, within the limits of experimental accuracy, activity of about 400 micro-curies per pin.

Three pins were selected for use in making three separate standards. The following procedure was followed identically in the manufacture of the three standards:

The irradiated pin was weighed on a Voland chemical balance, then partially dissolved in a known volume of hydrochloric acid. The pin was then weighed again, and the dissolved mass was established. (Several trial solutions were made to establish the time

necessary to dissolve a mass which would yield a deposit volume whose dissolved mass was approximately equivalent to the anticipated transfer mass.) A known volume of this solution (containing the anticipated transfer mass) was then deposited by micrometer pipette evenly along a 1/4" milled channel in a steel strip. The depth of this channel was .008" and the steel strip thickness was .015". The length of the deposit was equivalent to the circumference of the bearing cups to be used in the transfer experiment, the steel strip being slightly longer to allow for attachment to a ring by bending the excess length down through a cut across the circumference of a bearing cup.

This deposit was allowed to evaporate, leaving a known radioactive mass distributed evenly along the strip. The strip was then placed in the lead "castle" and counts were made at specified longitudinal positions to determine the activity at these positions. The strip was then removed, sprayed evenly with "Plastic 707" dielectric coating, replaced in the castle and counted again at the same positions. From this information, a per cent reduction of counts could be assigned to the coating (whose purpose was to prevent flaking and loss of the deposit when the strip was bent to the ring).

The three standard strips were then mounted individually on a ring, each was placed on the face-plate in the lead castle and counted. Excellent agreement (within 7% of the average) was obtained between the three values of counts per minute per milligram of deposited material, and the ring closest to the average value was selected as the standard ring.

It was now possible to accurately determine the activity per unit mass at any given time by counting the standard ring, correcting for unit mass, and correcting for the applied coating (4.2% reduction in counts in the case of the standard actually used).

This determination was made at the beginning and end of each running day.

APPENDIX B

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